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Method for determining a zero-point error of a Coriolis gyro

The invention relates to a method for determining the zero-point error of a Coriolis gyro.

Coriolis gyros, (which are also referred to as vibration gyros) are being used to an increasing extent for navigation purposes; they have a mass system which is caused to oscillate. This oscillation is generally a superimposition of a large number of individual oscillations. These individual oscillations of the mass system are initially independent of one another and can each be regarded in an abstract form as "resonators". At least two resonators are required for operation of a vibration gyro: one of these resonators (first resonator) is artificially stimulated to oscillate, with these oscillations being referred to in the following text as a "stimulation oscillation". The other resonator (the second resonator) is stimulated to oscillate only when the vibration gyro is moved/rotated. Specifically, Coriolis forces occur in this case which couple the first resonator to the second resonator, draw energy from the stimulation oscillation of the first resonator, and transfer this energy to the read oscillation of the second resonator. The oscillation of the second resonator is referred to in the following text as the "read oscillation". In order to determine movements (in particular rotations) of the Coriolis gyro, the read oscillation is tapped off and a corresponding read signal (for example the tapped-off read oscillation signal) is investigated to determine whether any changes have occurred in the amplitude of the read oscillation which represent a measure for the rotation of the Coriolis gyro. Coriolis gyros may be in the form of both an open loop system and a closed loop system. In a closed loop system, the amplitude of the read oscillation is continuously reset to a fixed value - preferably zero - via respective

control loops.

In order to further illustrate the method of operation of a Coriolis gyro, one example of a closed loop version of a Coriolis gyro will be described in the following text, with reference to Figure 2.

A Coriolis gyro 1 such as this has a mass system 2 which can be caused to oscillate and which is also referred to in the following text as a "resonator". This expression must be distinguished from the "abstract" resonators which have been mentioned above, which represent individual oscillations of the "real" resonator. As already mentioned, the resonator 2 may be regarded as a system composed of two "resonators" (a first resonator 3 and a second resonator 4). Both the first and the second resonator 3, 4 are each coupled to a force transmitter (not shown) and to a tapping-off system (not shown). The noise which is produced by the force transmitter and the tapping-off systems is in this case indicated schematically by the noise 1 (reference symbol 5) and the noise 2 (reference symbol 6).

The Coriolis gyro 1 furthermore has four control loops:

A first control loop is used for controlling the stimulation oscillation (that is to say the frequency of the first resonator 3) at a fixed frequency (resonant frequency). The first control loop has a first demodulator 7, a first low-pass filter 8, a frequency regulator 9, a VCO (voltage controlled oscillator) 10 and a first modulator 11.

A second control loop is used for controlling the stimulation oscillation at a constant amplitude and has a second demodulator 12, a second low-pass filter 13 and an amplitude regulator 14.

A third and a fourth control loop are used for resetting those forces which stimulate the read oscillation. In this case, the third control loop has a third demodulator 15, a third low-pass filter 16, a quadrature regulator 17 and a second modulator 18. The fourth control loop contains a fourth demodulator 19, a fourth low-pass filter 20, a rotation rate regulator 21 and a third modulator 22.

The first resonator 3 is stimulated at its resonant frequency 1. The resultant stimulation oscillation is tapped off, is demodulated in phase by means of the first demodulator 7, and a demodulated signal component is passed to the first low-pass filter 8, which removes the sum frequencies from it. The tapped-off signal is also referred to in the following text as the tapped-off stimulation oscillation signal. An output signal from the first low-pass filter 8 is applied to a frequency regulator 9, which controls the VCO 10 as a function of the signal that is supplied to it such that the in-phase component essentially tends to zero. For this purpose, the VCO 10 passes a signal to the first modulator 11, which itself controls a force transmitter such that the first resonator 3 has a stimulation force applied to it. If the in-phase component is zero, then the first resonator 3 oscillates at its resonant frequency 1. It should be mentioned that all of the modulators and demodulators are operated on the basis of this resonant frequency 1.

The tapped-off stimulation oscillation signal is, furthermore, passed to the second control loop and is demodulated by the second demodulator 12, whose output is passed through the second low-pass filter 13, whose output signal is in turn supplied to the amplitude regulator 14. The amplitude regulator 14 controls the first modulator 11 as a function of this signal and of a nominal amplitude transmitter 23 such that the first resonator 3 oscillates at a constant amplitude (that is

to say the stimulation oscillation has a constant amplitude).

As has already been mentioned, movement/rotation of the Coriolis gyro 1 results in Coriolis forces - indicated by the term FCcos(1 ·t) in the drawing - which couple the first resonator 3 to the second resonator 4, and thus cause the second resonator 4 to oscillate. A resultant read oscillation at the frequency 2 is tapped off, so that a corresponding tapped-off read oscillation signal (read signal) is supplied both to the third control loop and to the fourth control loop. In the third control loop, this signal is demodulated by means of the third demodulator 15, the sum frequencies are removed by the third low-pass filter 16, and the low-pass-filtered signal is supplied to the quadrature regulator 17, whose output signal is applied to the third modulator 22 such that corresponding quadrature components of the read oscillation are reset. Analogously to this, the tapped-off read oscillation signal is demodulated in the fourth control loop by means of the fourth demodulator 19, passes through the fourth low-pass filter 20, and a correspondingly low-pass-filtered signal is applied on the one hand to the rotation rate regulator 21, whose output signal is proportional to the instantaneous rotation rate, and which is passed as the rotation rate measurement result to a rotation rate output 24, and is applied on the other hand to the second modulator 18, which resets corresponding rotation rate components of the read oscillation.

A Coriolis gyro 1 as described above may be operated not only in a double-resonant form but also in a form in which it is not double-resonant. If the Coriolis gyro 1 is operated in a double-resonant form, then the frequency 2 of the read oscillation is approximately equal to the frequency 1 of the stimulation oscillation while, in contrast, when it is operated in

a form in which it is not double-resonant, the frequency 2 of the read oscillation differs from the frequency 1 of the stimulation oscillation. In the case of double-resonance, the output signal from the fourth low-pass filter 20 contains corresponding information about the rotation rate, while, when it is not operated in a double-resonant form, on the other hand, it is the output signal from the third low-pass filter 16. In order to switch between the different double-resonant/not double-resonant modes, a doubling switch 25 is provided, which connects the outputs of the third and fourth low-pass filters 16, 20 selectively to the rotation rate regulator 21 and to the quadrature regulator 17.

Unavoidable manufacturing tolerances mean that it is not possible to avoid the force transmitter system which stimulates the first resonator (stimulation oscillation) also slightly stimulating the second resonator (read oscillation). The tapped-off read oscillation signal is thus composed of a part which is caused by Coriolis forces and a part which is undesirably caused by manufacturing tolerances. The undesirable part results in the Coriolis gyro having a zero-point error whose magnitude is, however, unknown, since it is not possible to distinguish between these two parts when tapping off the tapped-off read oscillation signal.

The object on which the invention is based is to provide a method by means of which the zero-point error described above can be determined.

This object is achieved by the method as claimed in the features of patent claim 1. The invention furthermore provides a Coriolis gyro as claimed in patent claim 7. Advantageous refinements and developments of the idea of the invention can be found in the respective dependent claims.

According to the invention, in the case of a method for determining of a zero-point error of a Coriolis gyro, the resonator of the Coriolis gyro has a disturbance force applied to it such that a change in the stimulation oscillation of the resonator is essentially brought about, wherein a change in the read oscillation of the resonator by a partial component of the disturbance force is extracted as a measure of the zero-point error from a read signal which represents the read oscillation of the resonator.

In this case, the wording "resonator" means the entire mass system which can be caused to oscillate in the Coriolis gyro, that is to say, with reference to Figure 2, that part of the Coriolis gyro which is annotated with the reference number 2.

A major discovery on which the invention is based is that an artificial change to the stimulation oscillation resulting from the application of appropriate disturbance forces to the resonator can be observed in the tapped-off read oscillation signal: the change (modulation) of the stimulation oscillation also results in a change in the read oscillation because of the manufacturing tolerances of the Coriolis gyro. In other words: the disturbance force is applied essentially to the first resonator, but a partial component of this disturbance force is also applied to the second resonator. The "penetration strength" of a disturbance such as this to the tapped-off read oscillation signal is thus a measure of the zero-point error ("bias") of the Coriolis gyro. If, therefore, the strength of the disturbance component which is contained in the read signal is determined and is compared with the strength of the disturbance force (change in the stimulation oscillation), the zero-point error can be derived from it. A disturbance component signal which is proportional to the disturbance

component can then be used directly to compensate for the zero-point error.

The disturbance forces are preferably produced by disturbance signals which are supplied to appropriate force transmitters, or are added to signals which are supplied to the force transmitters. By way of example, a disturbance signal can be added to the respective control signals for control of the stimulation oscillation, in order to produce a disturbance force.

The disturbance signal is preferably an alternating signal, for example a superimposition of sine-wave signals and cosine-wave signals. Via corresponding force transmitters, an alternating signal of this type produces an alternating force which modulates the amplitude of the stimulation oscillation. The alternating signal is generally at a fixed disturbance frequency, so that the disturbance component of the tapped-off read oscillation signal can be determined by means of an appropriate demodulation process, which is carried out at the said disturbance frequency.

The disturbance frequency of the disturbance signal/the disturbance force preferably has a period which is substantially shorter than the time constant of the stimulation oscillation but is of the same order of magnitude as or is greater than the time constant of the Coriolis gyro. One alternative is to use band-limited noise as a disturbance signal instead of an alternating signal. In this case, the disturbance component is demodulated from the read signal by correlation of the noise signal with the signal which contains the disturbance component, (for example the tapped-off read oscillation signal).

The method described above can be used both for an open loop and for a closed loop Coriolis gyro. In the latter case, the zero-point error can be compensated for as

follows: a linear combination is formed of a controlled part of an alternating signal, which produces the stimulation oscillation, preferably including the disturbance signal, and an alternating signal which results in the read oscillation being reset, and this is passed to a rotation rate control loop/quadrature control loop for the Coriolis gyro. The controlled part is in this case controlled such that the change in the read oscillation, as determined from the read signal, becomes as small as possible as a result of the modulation (that is to say the disturbance component).

The disturbance component may, for example, be determined directly from the tapped-off read oscillation signal. The expression "read signal" covers this signal as well as the signal which is applied to a quadrature regulator in a quadrature control loop, or is emitted from it, and the signal which is applied to a rotation rate regulator in a rotation rate control loop, or is emitted from it.

The invention furthermore provides a Coriolis gyro which is characterized by a device for determining the zero-point error of the Coriolis gyro. The device has:

- a disturbance unit which applies a disturbance force to the resonator of the Coriolis gyro such that the stimulation oscillation of the resonator is modulated,
- a disturbance signal detection unit, which determines a disturbance component which is contained in a read signal (which represents the read oscillation) and has been produced by a partial component of the disturbance force, as a measure of the zero-point error.

If the disturbance force results from an alternating force at a specific disturbance frequency, the disturbance signal detection unit has a demodulation unit by means of which the read signal is subjected to

a demodulation process (a synchronous demodulation at the disturbance frequency). This results in the disturbance component being determined from the read signal. Alternatively, band-limited noise may be used as the disturbance signal.

The Coriolis gyro is preferably resetting, that is to say it has a rotation rate control loop and a quadrature control loop. In the case of a resetting Coriolis gyro, a control unit is advantageously provided in order to compensate for the zero-point error. The control unit produces a linear combination of a controlled part of an alternating signal, which produces the stimulation oscillation (preferably including the disturbance signal) and an alternating signal, which results in resetting of the read oscillation, and passes this collated signal to the rotation rate control loop/quadrature control loop for the Coriolis gyro. The linear combination of the signals is in this case controlled by the control unit such that the disturbance component of the read oscillation, as determined from the read signal, becomes as small as possible. The zero-point error of the Coriolis gyro is thus compensated for.

The disturbance signal detection unit preferably determines the disturbance component from a signal which is emitted from a rotation rate regulator in the rotation rate control loop, with the control unit in this example adding the linear combination of the signals to an output signal from the rotation rate regulator.

One exemplary embodiment of the invention will be explained in more detail in the following text with reference to the accompanying figures, in which:

Figure 1 shows the schematic design of a Coriolis gyro which is based on the method according to the invention; and

Figure 2 shows the schematic design of a conventional Coriolis gyro;

Figure 3 shows a sketch to explain the interaction of a resonator, a force transmitter system and a tapping-off system in a Coriolis gyro;

Figures 4a to 4d show a sketch to explain the forces and oscillation amplitudes for a Coriolis gyro with double resonance;

Figures 5a to 5d show a sketch to explain the forces and oscillation amplitudes for a Coriolis gyro near double resonance;

Figures 6a to 6d show a sketch to explain the method according to the invention.

In the drawings, parts and/or devices which correspond to those in the figures are identified by the same reference symbols, and will not be explained once again.

First of all, the general method of operation of a Coriolis gyro will be explained once again with reference to Figures 3 to 5, in the form of a vector diagram illustration (Gaussian plane).

Figure 3 shows, schematically, a Coriolis gyro, to be more precise a system 40 comprising a resonator (not shown), a force transmitter system 41 and a tapping-off system 42 in a Coriolis gyro. In addition, possible oscillations x (stimulation) and y (read) are indicated, which are coupled to one another by Coriolis forces as a result of rotations at right angles to the

plane of the drawing. The x oscillation (complex) is stimulated by the alternating force with the complex amplitude Fx (in this case, only the real part Fxr). The y oscillation (complex) is reset by the alternating force at the complex amplitude Fy with the real part Fyr and the imaginary part Fyi. The rotation vector exp(i*ω*t) are in each case omitted.

Figures 4a to 4d show the complex forces and complex oscillation amplitudes for an ideal Coriolis gyro with the same resonant frequency of the x and y oscillations (double resonance). The force Fxr and the stimulation frequency of the gyro are controlled so as to produce a purely imaginary, constant x oscillation. This is achieved by an amplitude regulator 14, which controls the magnitude of the x oscillation, and a phase regulator 10, which controls the phase of the x oscillation. The operating frequency ω1 is controlled such that the x oscillation is purely imaginary, that is to say the real part of the x oscillation is regulated to zero.

The Coriolis force during rotation, FC, is now purely real, since the Coriolis force is proportional to the speed of the x oscillation. If both oscillations have the same resonant frequency, then the y oscillation, caused by the force FC, is as illustrated in Figure 4d. If the resonant frequencies of the x and y oscillations differ slightly, then complex forces and complex oscillation amplitudes occur, as is shown in Figures 5a to 5d. In particular, this results in a y oscillation stimulated by FC, as shown in Figure 5d.

When double resonance is present, the real part of the tapped-off y signal is zero, but it is not if double resonance is not present. In both cases, the Coriolis force FC is zeroed in the case of reset gyros by a regulator for Fyr, which compensates for FC. In the case of Coriolis gyros which are operated with double

resonance, the imaginary part of y is zeroed by means of Fyr, and the real part of y is zeroed by means of Fyi. The bandwidth of the two control processes is approximately 100 Hz.

The method according to the invention will now be explained in more detail in an exemplary embodiment, and with reference to Figure 1.

A resetting Coriolis gyro 1' is additionally provided with a disturbance unit 26, a demodulation unit 27, a control unit 28, a fifth low-pass filter 29 and a multiplier 30.

The disturbance unit 26 produces an alternating signal at a frequency mod, which is added to the output signal from the amplitude regulator 14. As an alternative, band-limited noise can also be used as a disturbance signal instead of the alternating signal. Furthermore, this alternating signal is supplied to the demodulation unit 27. The collated signal which is obtained in this way (output signal from the amplitude regulator and alternating signal) is supplied to a (first) modulator 11, whose corresponding output signal is applied to a force transmitter (not shown), and thus to the resonator 2. In consequence, an alternating force which corresponds to the alternating signal is also applied to the resonator 2. This alternating force can be observed, after "passing through" the resonator 2, in the form of a disturbance component in the tapped-off read oscillation signal. In this example, in order to determine the disturbance component, the signal which is emitted from the rotation rate regulator is subjected to a demodulation process which is carried out by the demodulation unit 27 and which takes place at the frequency ω_{mod} (disturbance frequency). The signal (disturbance component) obtained in this way is filtered by the fifth low-pass filter 29 and is supplied to the control unit 28. The signal

which is supplied to the control unit 28 represents a measure of the zero-point error. The control unit 28 produces an output signal as a function of the signal that is supplied to it, which output signal is supplied to the multiplier 30 and is in such a form that the disturbance component of the tapped-off read oscillation signal is controlled to be as small as possible. The multiplier 30 multiplies the collated signal (output signal from the amplitude regulator and alternating signal) which is supplied to it by the output signal from the control unit 28, and thus produces an output signal which is added to the signal that is emitted from the rotation rate regulator. In consequence, the bias of the Coriolis gyro is reset. The signal which is supplied to the demodulation unit 27 may alternatively also be the signal which is supplied to the rotation rate regulator 21, or which is supplied to the quadrature regulator 17/is emitted from the quadrature regulator 17. The signal which is supplied to the demodulation unit 27 may also be the tapped-off read oscillation signal itself. In the latter case, the operating frequency ω must also be taken into account during the demodulation process.

Furthermore, in principle, it is possible to feed the output signal from the multiplier 30 into the rotation rate control loop at any desired point (not only directly upstream of the second modulator 18), that is to say at any desired point between the point at which the read oscillation is tapped off and the third modulator 22. Analogous considerations apply to the feeding of the disturbance signal into the quadrature control loop.

The method according to the invention which has just been described can also be explained as follows, with reference to Figures 6a to 6d:

The read oscillation will in general "see" a small proportion of the stimulation force Fxr: kFyx*Fxr as a result of manufacturing tolerances. When the Fyr control loop is closed, Fyr is thus changed by kFyx*Fyr in comparison to the correct value. This results in a corresponding bias, since Fyr is a measure of the rotation rate. In order to compensate for this error, the amplitude of Fxr is now modulated without any mean value by means of the disturbance unit 26. The modulation frequency or the frequencies of the band-limited modulation noise should be chosen such that the stimulation oscillation is disturbed as little as possible, but the rotation rate control loop is disturbed as strongly as possible, via the component KFyx*Fxr. The error component in Fyr, kFyx*Fxr is now compensated for by addition of a controlled component kFyxcomp*Fxr to Fyr in such a way that the modulation in the rotation rate channel disappears. This is done by controlling kFyxcomp, which is emitted from the regulator unit 28 (preferably by software). The input signal to a corresponding regulator (the regulator unit 28) is the signal of Fyr, demodulated synchronously with the modulation frequency. When the regulator is matched, the modulation signal in the rotation rate channel disappears, and there is thus no need for a blocking filter for the modulation frequency in the rotation rate output.